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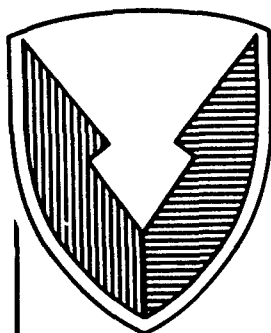
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C E N T E R

Technical Report



No. 13338

COOLING DEVICE FOR COMBAT VEHICLE

CREW DRINKING WATER

(Phase I)

CONTRACT NUMBER DAAE07-87-C-R052

MARCH 1988

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<p>The objective of this SBIR A87-156 Phase I Project was to evaluate the feasibility of a Drinking Water Cooling System for combat vehicle crews that can maintain a water temperature of 75°F, when the exterior temperature is as high as 120°F and under the all-buttoned-up condition the vehicle internal temperature can be as high as 150°F. The crew's water canteen is affected by that high temperature and it is very difficult to encourage the crew to drink a sufficient quantity of water to maintain their body electrolyte balance.</p> <p>The concept incorporated a compound system consisting of a Thermal Electric Cooler (TEC) in series with a Water Evaporative Cooler (WEC). A WEC system alone cannot cool the air from 150°F to 70°F, while the TEC system alone cannot operate effectively at heat rejection temperature higher than 160°F, but the two in series will make the system work well. (to be continued)</p>					
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This study is aimed at the proof of the working principle and the collection of data to make the novel system compact and requiring very little energy. Two breakthroughs were introduced during the study, 1) the use of a super saturated water mist in air created by an ultrasonic cooler and 2) the use of a heat pipe to extract the heat from the water.

Experimentally, a 1-gallon plastic foam-insulated water container, equipped with bread-board electric circuitry and controls, was tested at representative temperature and humidity of the all-buttoned-up vehicle environment. The test results verified the fact that the TEC would work only in conjunction with an evaporative air cooler. A sufficient amount of data were obtained for the Phase II product development for sizing and for power circuit and control system design for the future product.

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1.0 INTRODUCTION

This final technical report describes the results of the SBIR Phase I study of a cooling device for combat vehicle crew drinking water, performed by Cheng Technology and Services, Inc. under contract No. DAAE07-87-C-R052 for the U.S. Army Tank-Automotive Command, TACOM. The Phase I study was a research effort to conceive and evaluate a cooling system that would function under the highest temperature conditions that could be encountered inside of the vehicle in either low or high humidity environments, and that would withstand the relatively high accelerations expected under combat conditions over rough terrain.

Under very hot weather conditions in certain areas the ambient temperature outside the vehicle can be as high as 120 °F and interior temperature can reach 150 °F. At present the crew's uncooled drinking water canteens are affected by the high interior temperature. It is essential to the maintenance of high crew efficiency that the crew drink a sufficient amount of water to keep up the body's electrolyte balance. Experience has shown that under such high-temperature environmental conditions personnel will not voluntarily drink water that is much above 70 °F. The cooling of crew drinking water is, therefore, necessary to the maintenance of high crew proficiency. It is desirable that drinking water cooling be accomplished with very low power consumption. It is also important to design a system that is sufficiently small that it will not require large additional space inside the vehicle to accommodate the cooling system.

During the proposal stage, it was pointed out that with the higher ambient temperatures in desert areas the air is very dry, and a water evaporative cooler is very effective. However, in the high-humidity areas of the world, the temperature rarely becomes higher than 105 °F, but evaporative cooling is much less effective. Therefore, a thermal electric cooling (TEC) system in series with a water evaporative cooler (WEC) system was proposed. The thermal electric cooler by itself has all the smallness and the advantages of non-moving parts which are desired, but could not operate effectively at heat rejection temperatures higher than 160 °F. Therefore, if the WEC can cool the air down from 150 °F to 120 °F and the TEC could reject the heat around 150 °F, there would be a 30 °F temperature difference to make a compound system work with sufficiently small cooling fin area.

2.0. OBJECTIVES

The overall objective of the Phase I effort was to conceive and evaluate the feasibility of a crew drinking water cooling system for combat vehicles. During the proposal stage, it was clearly stated that, for a combat crew drinking water cooling system to have low power consumption, it must be compact and contain no major moving parts. The system envisioned and proposed involved a combination of thermal electric and water evaporative cooling systems. The Phase I effort concentrated on establishing the feasibility of the underlying operational principles, assessing the product feasibility, and acquiring component performance data needed for detail design and sizing in the Phase II development effort. A series of tests were required to accomplish these objectives and the tests are described in the discussion section of this report.

3.0. CONCLUSIONS

3.1. General

The Phase I objective of this research and development project to investigate the feasibility of using a newly identified compound cooling cycle to cool drinking water for combat vehicle crews under very hot, all-buttoned-up conditions has been attained. Such a system is now proven to be feasible. Such a system can be:

- o assembled with no moving parts (except for a small fan)
- o a compound cycle
- o self-regulating
- o safe
- o rugged
- o lightweight

The system understanding and technology status is now ready to go forward into Phase II with confidence and a high likelihood of success.

3.2. Water Container

The water container must be highly resistive to transmitting heat so that the cooled water will not lose heat to the high temperature environment. Thermos bottles, having an

internal water container and an external protective covering separated by a vacuum space, are the obvious candidates for use. Two such thermos bottle concepts were considered, those with internal water containers of a) glass or b) stainless steel. A third concept, in which the water container is plastic and the vacuum space is replaced by plastic foam, was also considered. The glass thermos has the highest performance (lowest heat transfer coefficient) but is considered too fragile for application inside a combat vehicle. The stainless steel thermos, which has a heat transfer coefficient approximately twice that of the glass thermos, is preferred for the vehicular use because it is rugged. The plastic container which has a heat transfer coefficient over 5 times that of the glass thermos and is not as rugged or long lived as the stainless thermos, was rejected. The stainless steel thermos concept was selected for actual use. It should be noted that the plastic container was used for Phase I testing because it cost less and because its high heat transmission rate resulted in reduced test times relative to the higher performance containers.

3.3. Compound Cooling System

The Phase I proposed system was a compound system consisting of a thermal electric cooler (TEC) and a water evaporative cooler (WEC). The compound system was foreseen to be required to obtain satisfactory performance at the highest vehicle interior temperature for a range of container water levels from near empty to full. The need for the compound system was confirmed during the Phase I effort.

3.4. New Technology Developments

During the course of the study, new, improved technologies were introduced and as a result the system works even better than was originally thought possible. These improved technologies are interactive in that one causes improved performance of the other.

3.4.1. Thermal electric cooler (cooled finger). One improved technology breakthrough resulted from making the cooled finger in the form of a diode configured, electrically heated heat pipe. The cooled finger originally was thought of as a simple copper rod with fins on one end for heat dissipation to the surrounding air, with the other end immersed in the water which is to be cooled. Initial tests showed that the fins did not help much because the heat transfer was being limited by the heat conduction through the copper rod, especially when the water level was low. It then became clear that using a lightweight heat

pipe could eliminate this problem, and a heat pipe was used in the later tests. The use of the heat pipe was found to cut down the temperature difference required between the thermal electric cooler and the end of the cooled finger. The effectiveness of the heat pipe over the same diameter copper rod was greater by a factor of about 100 for the same temperature difference. If the heat pipe is constructed as a thermal diode, the control of the thermal electric cooling system will be greatly simplified because the diode construction will allow heat to flow much easier in one direction than the other.

3.4.2. Water Evaporative Cooler (ultrasonic evaporator). A second improved technology breakthrough resulted from incorporating an ultrasonic agitator with the water evaporative cooler. The use of the ultrasonic evaporator cools the ambient air below its wet bulb temperature, thereby providing even larger effective temperature differences for conductive cooling by the thermal electric cooler. This kind of a system would ease considerably the mechanical packaging problems for both power-on and power-off conditions, however this is a new and unexplored technology and there was neither sufficient time nor funds to conduct a thermal diode heat pipe test in Phase I.

3.5. Sizing of Components and System

During the Phase I study, it was found that the system can be more easily packaged into a much smaller volume than originally thought if a wicking evaporative system is incorporated. Sufficient performance data was obtained on the several components to provide for making sizing decisions with confidence that the resultant performance will be as desired. The Phase II prototype detail design and product development can now proceed in an efficient manner.

3.6. Performance

A compound water cooling system based on the model that was tested in Phase I would be very effective in all combat environments for combat vehicles. In very humid weather, the outside temperature would seldom be higher than 105 °F, but in the all-buttoned-up condition the crew would perspire due to the high inside temperature. However, for the compound cooling system being evaluated in this work, the cooler cabinet temperature will remain lower than 115 °F. This is due to the high heat capacity of the water moisture in the air. At that temperature, the newly invented TEC and ultrasonic WEC compound cooling system should function very well. This results from the upper temperature of the

cooling fin having at least a 30 °F temperature differential to provide for heat rejection.

The system design is focused on the more critical condition that occurs when the external ambient temperature is 120 °F and dry, where the vehicle all buttoned up inside temperature could be as high as 150 °F. It has become obvious that the only system which could function well under this condition is the compound cooling system. The above results were based only on the feasibility study test unit data. During Phase II the production cooling system must be properly sized for the real application. There is potential for compactness, there are no moving parts for heat pumping and the power consumption of the system is quite low. It was found during the room temperature operation that the system is extremely efficient. It can cause one gallon of water to drop its temperature 12 °F in the first half hour. The power equivalent for pumping heat is 61.5 watts. The actual power put into the TEC was only 87.2 watts and the power required by the ultrasonic evaporator is about 35 watts. The resultant overall coefficient of performance is about 2.0. This is better than most of the mechanical refrigeration systems. The situation changes when the system is subject to a very high temperature of 150 °F. The total heat pumping rate would be the sum of heat transferred from the outside plus the temperature drop of the water. In the feasibility test setup the water container used had the poorest heat protection ability of the three types available but was selected for its convenience. In this case, the heat transfer from the outside was calculated to be about 16.1 watts and the cooling under the high-temperature environment was only about 10 watts. So, the total heat pumping rate was 26 watts. During the test, the electrical power input was about 68 watts to the TEC and about 30 watts to the ultrasonic evaporator. The total electric power used was 98 watts to pump out 26 watts of heat. So the coefficient of performance was about 1.36.

Considering that a mechanical system would also drop its coefficient of performance at high temperatures, the above performances are very good in comparison, especially since none of the mechanical cooling systems could be used in such a harsh environment.

3.7. Basis for Conclusions

During Phase I of the project , the following were accomplished:

- developed a design and established the heat transfer characteristics of the evaporative cooler components.

- developed a design and established the heat transfer characteristics of the cooled finger.

- conducted a quantitative heat transfer analysis of the system for future sizing purposes.

- established operating criteria for the compound cooling system.

- designed and tested the power and control system for the combined ultrasonic water evaporator and thermal-electric cooling system.

- performed actual test of the bench model in an environmental chamber.

The conclusions cited herein are based on the results of all of these Phase I activities and are deemed by the contractor to provide a sufficiently solid base on which to proceed into Phase II.

4.0 RECOMMENDATIONS

The following recommendations are made relative to the Phase II effort:

- Proceed with the Phase II effort, from the standpoint of technology readiness and Phase I results indicating a very high likelihood of success.

- Allow for acquisition and test of a thermal diode configuration of the cooled finger to complete the available design data required for the final design of the prototype unit.

- Design the prototype unit to the size and shape restrictions imposed by the designated space available inside the assigned vehicle, with consideration being given to other possible combat vehicle applications.

- Design the water container to include a metal vacuum jacket for heat insulation and with a hardened structure.

- Provide a sturdy tie down arrangement making the unit removable for maintenance, repair or replacement, but give consideration in the design to the user friendly aspect so that crews will have easy access to the water without moving the water container.

- Design the thermal electric cooler, the water evaporative cooler and the associated power and control system as hardened mating units that will assure reliable operation in the high temperature, high dynamic load environment, but that can be readily separated from the water container and easily accessible for maintenance and repair.

5.0. DISCUSSION

This discussion covers the details of the tasks undertaken in carrying out the Phase I effort.

5.1. Water Container

The proposed system involves active cooling to extract heat from the water within the container. The container itself must be highly resistive to transmitting heat, thereby maintaining the low internal temperature of the water by avoiding transmission of heat from the surrounding high temperature air through the container to the cooled water. During the course of this study, three types of heat protective water containers were evaluated. The best thermal performance is afforded by the traditional glass thermos, and the poorest is the plastic foam-insulated system. The glass thermos, while having the best performance, is too easily broken under the high dynamic load environment of a combat vehicle. Therefore, the recommended system for the Phase II military prototype is a vacuum double-jacketed metal thermos, as reported in the first progress report. The heat protective coefficients measured in the Phase I tests are summarized in Table 5-1.

If the surrounding internal ambient temperature is 150 °F and the water has to be maintained at 70 °F in a 1-gallon plastic water container with foam insulation, then at least 66 Btu/hr has to be pumped out of the system, as the surface area is approximately 1.57 ft.². That means the temperature maintenance pumping wattage should be at least 21 watts. The wattage of the thermal electric unit would be at least twice that if the coefficient of performance for the cooling system is 2.0. A metal vacuum thermos, however, could have the same performance at one-third the power requirement. During the course of the Phase II prototype development, the trade off power versus the price of constructing the vacuum thermos and the military specification mechanical requirements will determine the final choice of the 5-gallon water container construction.

Table 5-1 Typical Water Container Heat Transfer
Coefficients

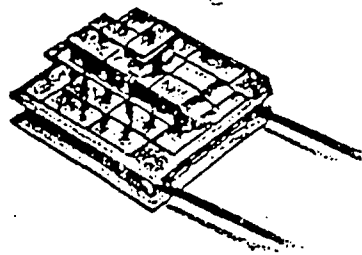
<u>Type</u>	<u>h, Btu/ft²/°F/hr</u>
Glass Thermos	0.0905
Stainless Steel Thermos	0.1724
Foam Insulated Thermos	0.527

5.2. Thermal Electric Cooler Evaluation

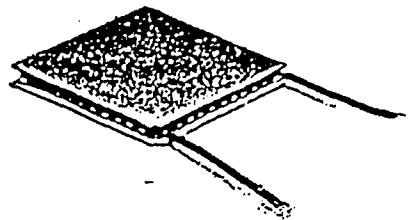
The TEC is the heart of the cooling system. It is a solid state device with the thermodynamic properties of thermal couples. The differences between the TEC and the thermal couple (TC) are: 1) the TEC can carry an electric current about a thousand times that of TC 2) the TEC works in a very narrow temperature difference range in contrast to that of a TC and 3) the internal resistance is much higher for the TEC and is non linear with temperature.

With the above property difference, a TC becomes a temperature measurement device and the TEC becomes a heat pumping device. The coefficient of performance of the TEC can be as good as two, which is comparable to mechanical heat pump systems. Because of its small size and high reliability, the TEC is far superior to a mechanical system. The mechanical system also has limitations in operating temperature depending on the choice of its working fluids. In general, the rejection temperatures are limited below 180 °F to ammonia or freon as heat pumping media. The geometry of TEC units is shown in Figure 5-1.

To summarize the TEC properties, it is useful to refer to a typical performance chart such as that presented in Figure 5-2. It can be seen that at high electric currents the TEC will withstand high-temperature differences, but the internal heat generation by the electric current (current square times the internal resistance I^2R) will reduce the heat pumping capacity to zero. If a very high heat removal rate can be obtained, the temperature difference would have to be very small. If that is indeed the case, no heat pumping would even be necessary. To make use of the TEC device, an operating point has to be chosen--it would be the desired final water temperature of 70 °F. With a high upper heat rejection temperature of 150 °F the evaporative cooler could take over. Otherwise the ambient temperature would have no cooling potential. For example, a TEC model CP1.4-127-06 can have a maximum current of 6.0 amperes and withstand temperature differences 120 °F, but the best operating condition would be 3.0 to 3.5 amperes for this application.



Cascade Module



Single Stage Module

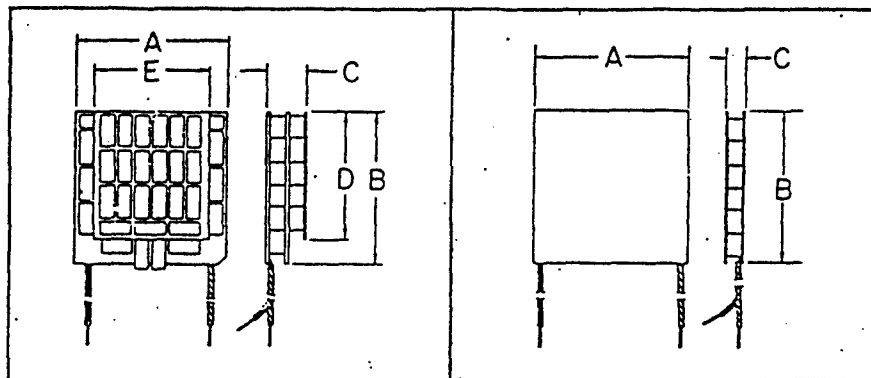


Figure 5-1 Thermal Electric Cooler Geometry

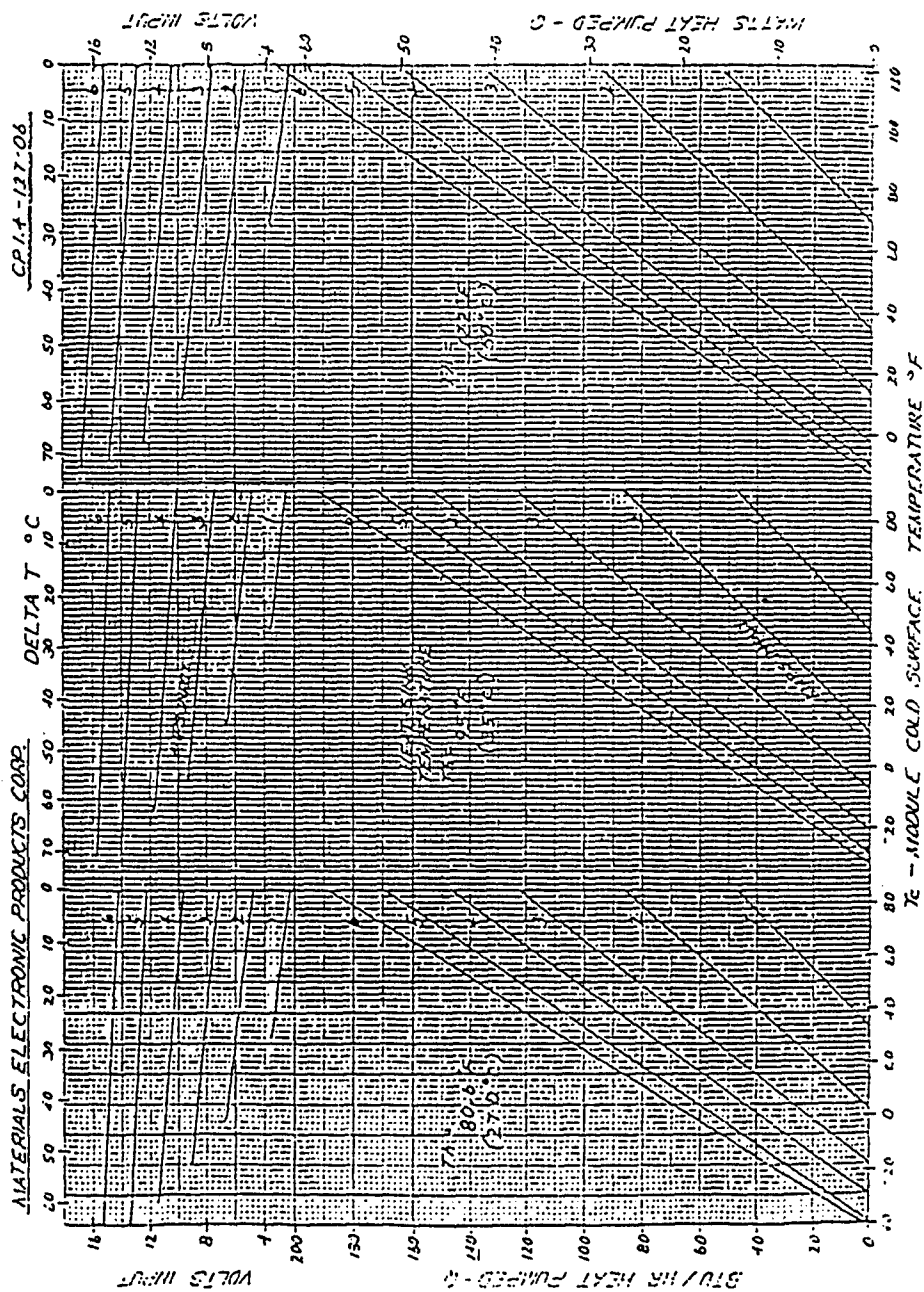


Figure 5-2 Thermal Electric Cooler Performance

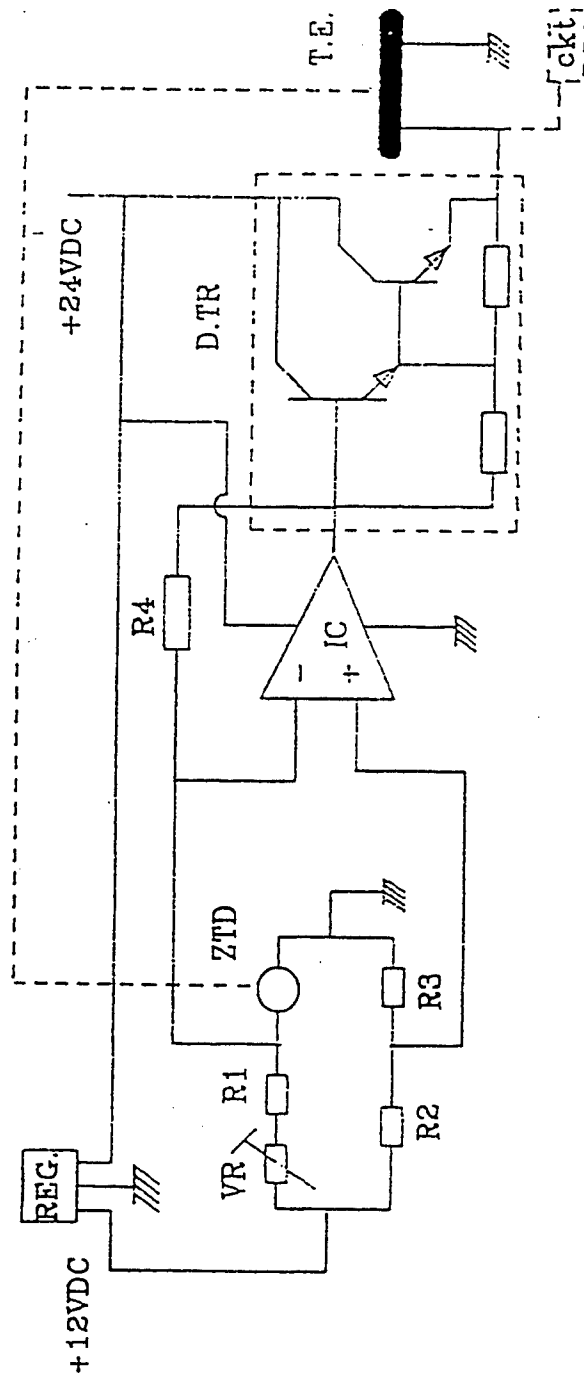
5.3. Power and Control Systems

The power system required for the TEC can be tailored to 24-volt systems and the required electrical current would be small during the temperature maintenance operation. During the heat pumping phase, the required current would depend upon the choice of pumping rate. If 5 gallons of water were sitting in a vehicle at the highest filling temperature of 100 °F, the total heat that would have to be removed in an hour to cool the water to 70 °F would be 120 Btu plus 60 Btu to balance the heat input from the 150 °F ambient air. The ideal design would require a pumping rate of 180 Btu/hour. This is about 60 watts, and if the Coefficient of Performance (COP) is 2 then the TEC selected should have a maximum of 120 watts electric input. The ultrasonic cooler requires a small fan and power to drive the ultrasonic crystal. The maximum power required for that would be 40 watts. Therefore, from the current research results, the power required for the Phase II 5-gallon system will still be very low.

The control system for the power unit was designed and bread-board tested during Phase I. The circuit senses the water temperature, and until it reaches 75 °F, the pumping power will be fully on. At this point, the power will be reduced gradually to the maintenance power level in proportion to the temperature difference between the water and the final temperature setting. The system has been used for all the testing conducted during Phase I. A circuit diagram for the system is presented in Figure 5-3.

5.4. Cooled Finger Evaluation

A cooled finger system has been incorporated to cool the water in the container. This system not only has to cool the water when the container is full, but also has to cool effectively when the container is half full or close to empty. The distance for heat conduction from the TEC is short when the container is full, and would be much longer when the container is half full. Finned copper conducting rods first were tested. It was very clear from the tests that fins do not help because the heat transfer was being limited by the heat conduction through the copper rod. It was at this point it became clear that using a lightweight heat pipe could eliminate this problem. During the final 2 months of the study, a heat pipe only was used for the cooled finger configuration.



R1: 10 Kohm R2: 10 Kohm R3: 10 Kohm R4: 100 Kohm
 VR: 5 Kohm ZTD: 10 Kohm REG: LM78L12 IC: LM1458
 D.T.R: MJ11012 T.E.: CP1.4-71-06L & CP1.4-127-06L

Figure 5-3 TEC Power and Control Circuits

5.5. Heat Pipe Evaluation

The heat pipe is an advanced heat transfer device for which the technology is advancing rapidly because of widespread interest in many different applications. Its principle involves the fact that heat is transferred by evaporating a liquid into vapor, and characteristic of its operation is that large quantities of heat can be absorbed without temperature increases. The vapor is convectively transported down to the cooled end where it recondenses into liquid, releasing a large quantity of the latent heat during this phase transition. Since convective transport does not require a temperature gradient, effectively the heat conductivity has been dramatically increased. The liquid at the cooled end is then soaked up by a wick and transmitted back to the hot end by capillary action to complete the cycle. The heat pipe used in this project had a 1/2-inch diameter and used an alcohol-water mixture as a working fluid which was selected for the temperature range of this project. The use of the heat pipe cuts down the temperature differences required between the TEC and the end of the cooled finger. A typical temperature difference of 4 °F instead of 20 °F was observed, but the heat pipe conducted more heat away than did the solid copper finned cooled fingers. The effectiveness of this heat pipe over the same diameter copper rod is greater by a factor of about 100. A typical cross section of the heat pipe can be seen in Figure 5-4.

It is desirable to have a mechanical electrical switch between the cooled finger and the TEC so when power is being cut off, heat would not be transferred from the TEC to the water again. This point was viewed in two ways: 1) in the high-temperature environment, power will never be cut off, and 2) a heat pipe constructed as a thermal diode can be used for this project that would allow heat to flow in one direction much easier than the other direction. This thermal diode will eliminate the need to thermally isolate the electrical switch. To function in this manner the heat pipe will have the wick portion extending only half way down the heat pipe. If the cooled end is the unwicked end, then the liquid after condensation would not be able to be sucked back to the hot end. This in effect interrupts the heat pipe action. Obviously, the heat pipe still works if the heat transfer is in the other direction. A cross sectional view of a typical heat diode is shown in Figure 5-5. The heat pipe is not limited to a simple round configuration, but it could be built as flat plate, curved-surface systems. This concept will provide all the flexibility needed for the prototype development in Phase II.

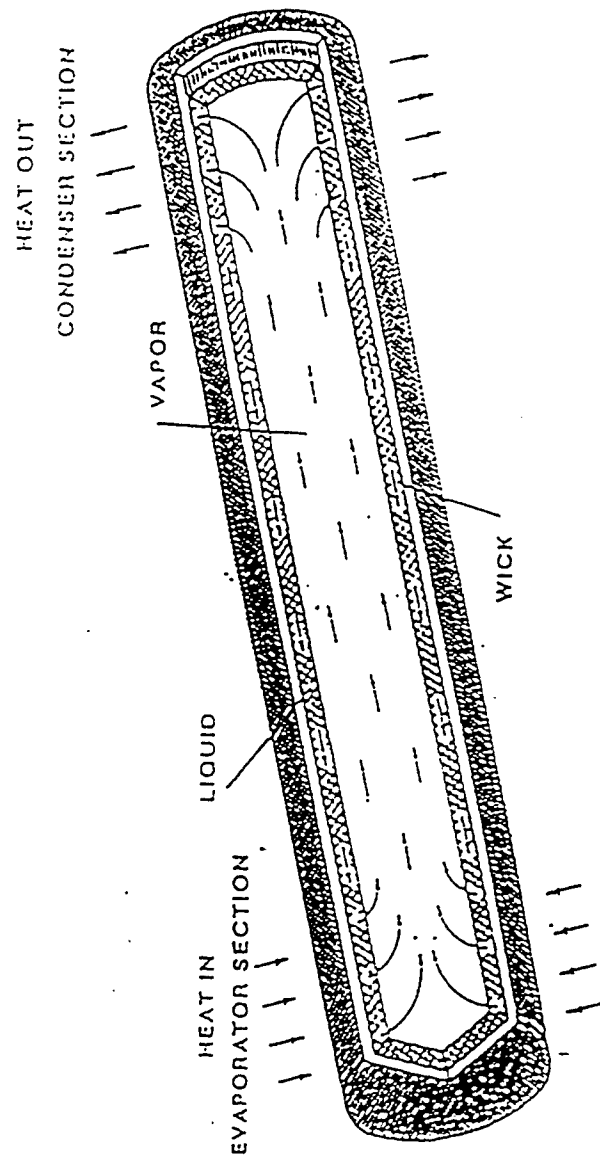


Figure 5-4 Heat Pipe Principle

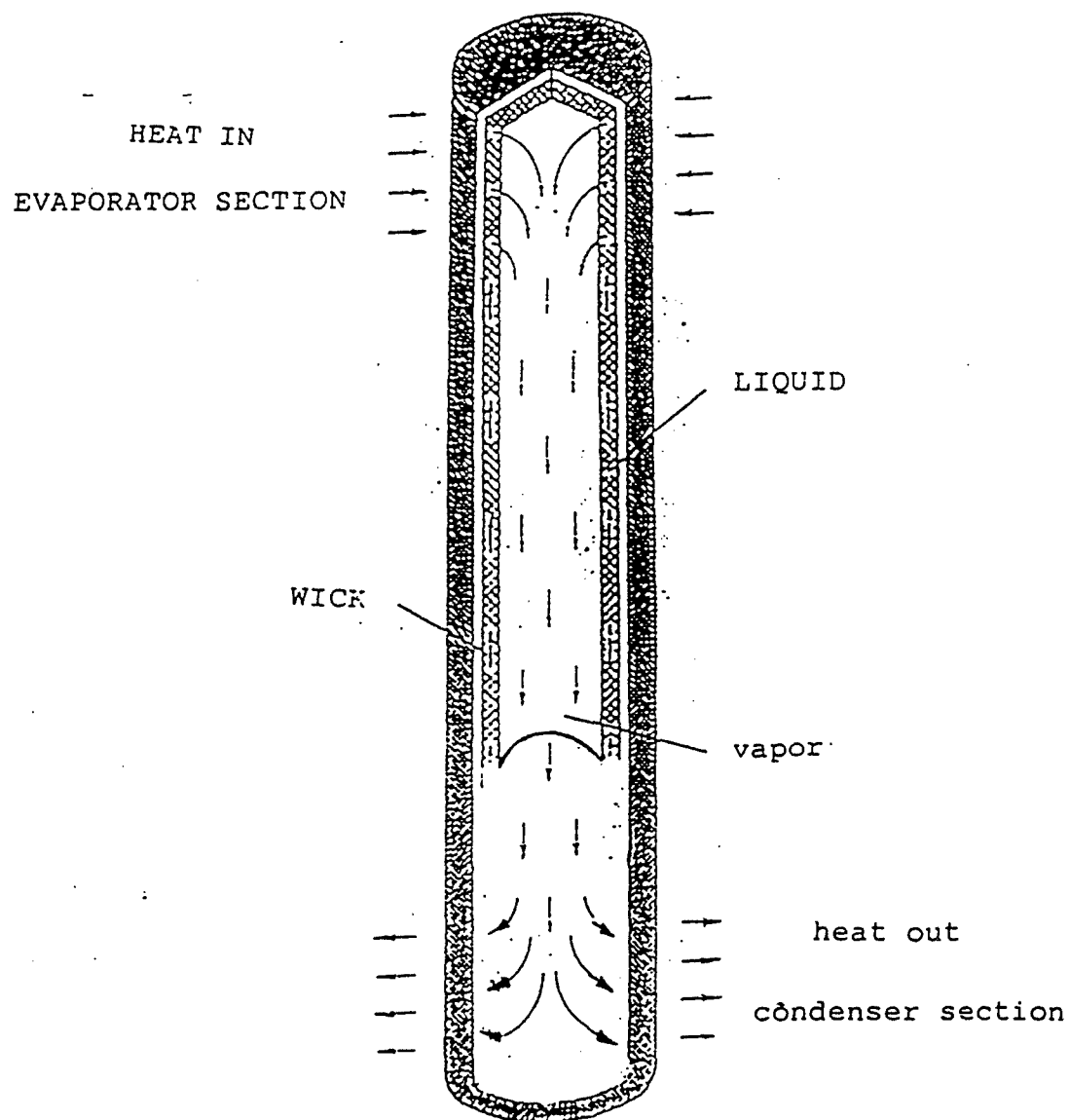


Figure 5-5 Heat Diode Principle

5.6. Comparison Between Wicking and Ultrasonic Cooler

In the original proposal, a wicking system was thought to be adequate as an air cooling system.. This was because the hot ambient condition and the all-buttoned-up vehicular cabinet were always associated with low relative humidity conditions. Wicking systems commonly have been used in hot desert areas such as in Southern Arizona, etc., for air conditioning.

During the feasibility study, it was recognized that the air cooled by wicks soaked with water can only be cooled down to the wet bulb temperature. It was further realized that when the vehicular cabinet temperature reaches 150 °F the relative humidity can be increased due to the evaporation of the crew's perspiration, so, the wicking cooling system could only cool the air down to 110 °F in this practical situation. This is adequate to cool the heat rejection fins of a TEC unit but is not sufficient to make it possible to further reduce the fin area to make the unit more compact. The technology of using an ultrasonic evaporator can be much more superior in this situation. The ultrasonic evaporator dislodges a lot of small water droplets into air by the use of ultrasonic waves breaking the surface tension of the water surface. The water droplets will evaporate in sufficient quantity to reach the wet bulb temperature. In addition, a lot of water droplets are formed that cannot be evaporated because the air has reached its saturation point. The remaining droplets can absorb some more heat to reach an equilibrium super-saturation temperature, which drives the air to a new temperature below the wet bulb temperature. If this is indeed the case, it will provide an added advantage when this super-saturated air vapor mixture passes through the cooling fin passage. The remaining droplets will then be evaporated, absorbing large quantities of heat with only a very small temperature increase. This can compound the effectiveness of reducing the required cooling fin surface area. A schematic drawing of an ultrasonic evaporative cooling system is shown in Figure 5-6.

The amount of water used by the ultrasonic evaporator can be controlled electronically, therefore, the total water consumption for cooling purposes would also be reduced. During the last 4 months of the Phase I experimental study, only the ultrasonic evaporator was used to cool the ambient air. This cooled air was then used to cool the TEC. The findings were even more surprising during the high-temperature environmental chamber tests, as will be described later.

The power consumption of the ultrasonic circuit is small and it is more suitable for the 24-volt dc system than the 12-volt system. A typical circuit diagram is shown in Figure 5-7.

5.7. Integration of the Thermal Electric Cooler with the Ultrasonic Water Evaporative Cooler to form a Compound System

The ultrasonic evaporator is shown in Figure 5-8 and the integrated drinking water cooling system can be seen in Figures 5-9 and 5-10. The package is small, partially surrounding a commercial 1-gallon plastic foam-insulated container. This compound system was evolved because the TEC system alone has a high-temperature operation limitation and the water evaporation system can cool the air only down to near the wet bulb temperature. However, a combination of the two systems results in an ideal compound system for this application. A further advantage of the compound system was found relative to the mechanical package sizing. If the vehicular cabinet temperature is indeed 150 °F, then the heat rejection temperature would have to be 180 °F in order to have enough temperature difference to reduce the cooling fin surface area to a reasonable size. If the targeted water temperature is 70 °F, then the temperature gradient the TEC has to maintain would be 110 °F. This is beyond a single-stage TEC's operating range. Cascading TEC's are common, But this is only for subzero temperature operations. The TEC, due to its current design, is limited to operation below 160 °F. On the other hand, to design a new system for future use, the compound evaporator and TEC can remove the constraint of the ambient temperature as a heat rejection limitation.

Earlier the integration of the TEC and an ultrasonic evaporation system were tested and the results were reported along with cooled finger configuration tests. In early November, 1987, a supplemental report was submitted using a heat pipe as cooled finger with greater success. In the final period, the extensive environmental tests were made in a simulation chamber capable of providing a controlled temperature and humidity. The following sections will describe the simulation chamber tests and their results.

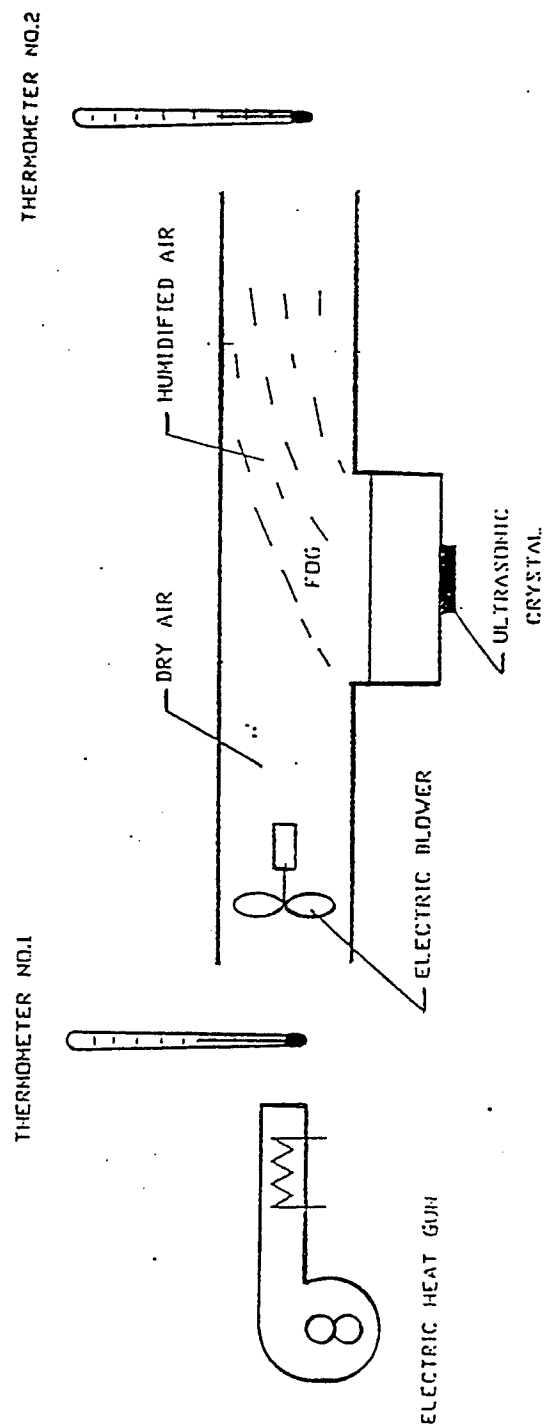
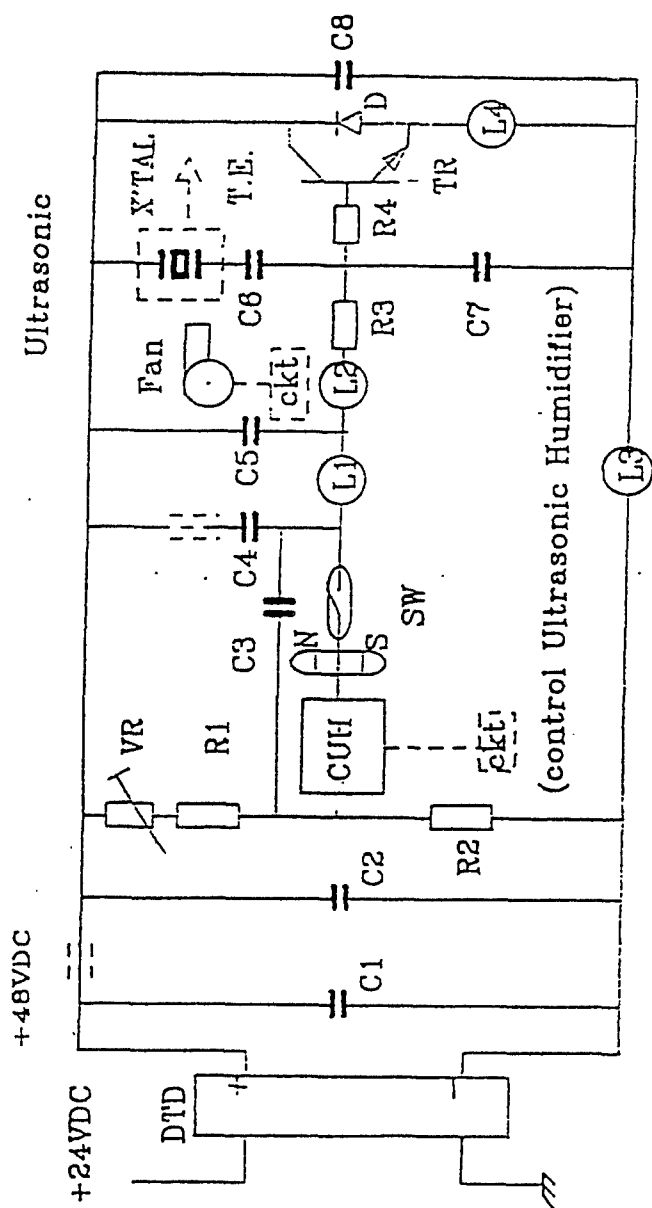


Figure 5-6 Ultrasonic Evaporative Cooling System Schematic



- R1: 4.7 Kohm R2: 6.8 Kohm R3: 6.9 ohm R4: 2 ohm
 VR: 10 Kohm D: 1N4007 TR: C2098
 SW: Water Level Switch X'TAL: Ultrasonic Transducers
 L1: 0.1 mh L2: 0.1 mh L3: 0.3 mh L4: 0.01 mh
 C1,C2,C3: 102 C4,C5: 103 C6: 473 C7: 334 C8: 102
 DTD: 24VDC to 48VDC Fan: V483L

Figure 5-7 Ultrasonic Evaporator Typical Circuit Diagram

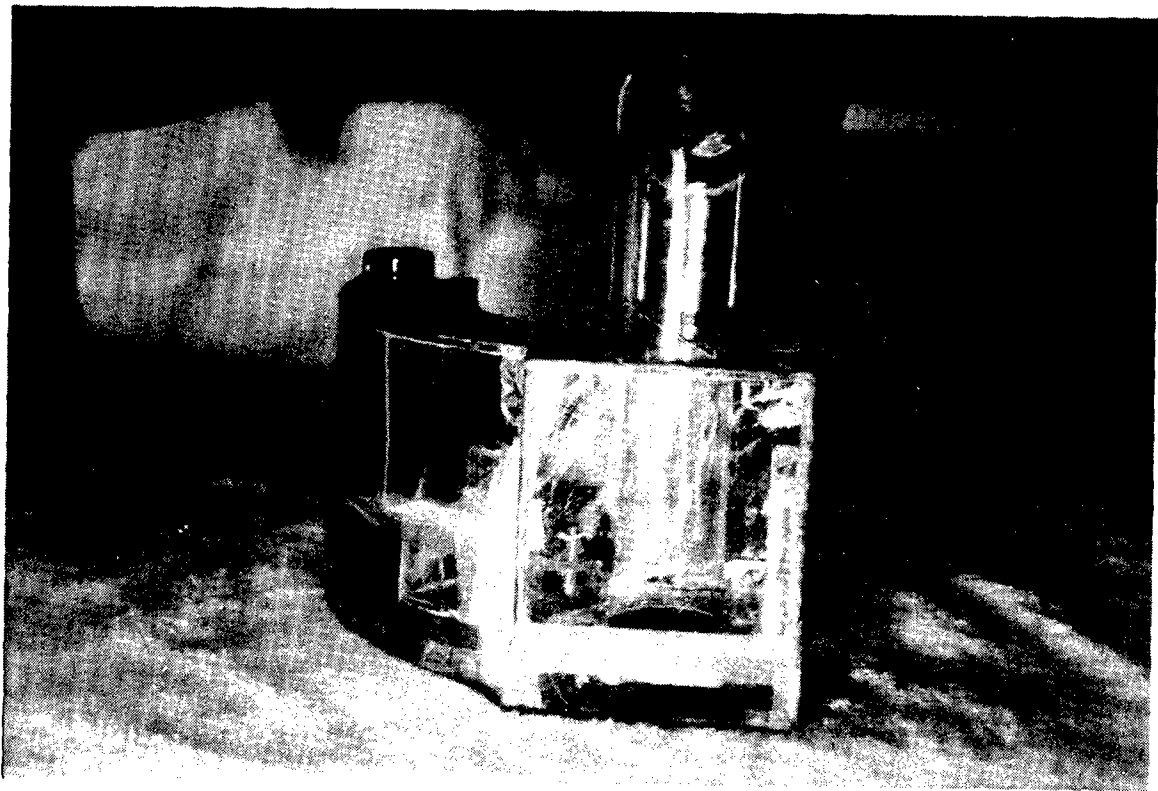


Figure 5-8 Ultrasonic Cooler



Figure 5-9 Assembled View of the Water Container and Cooling System

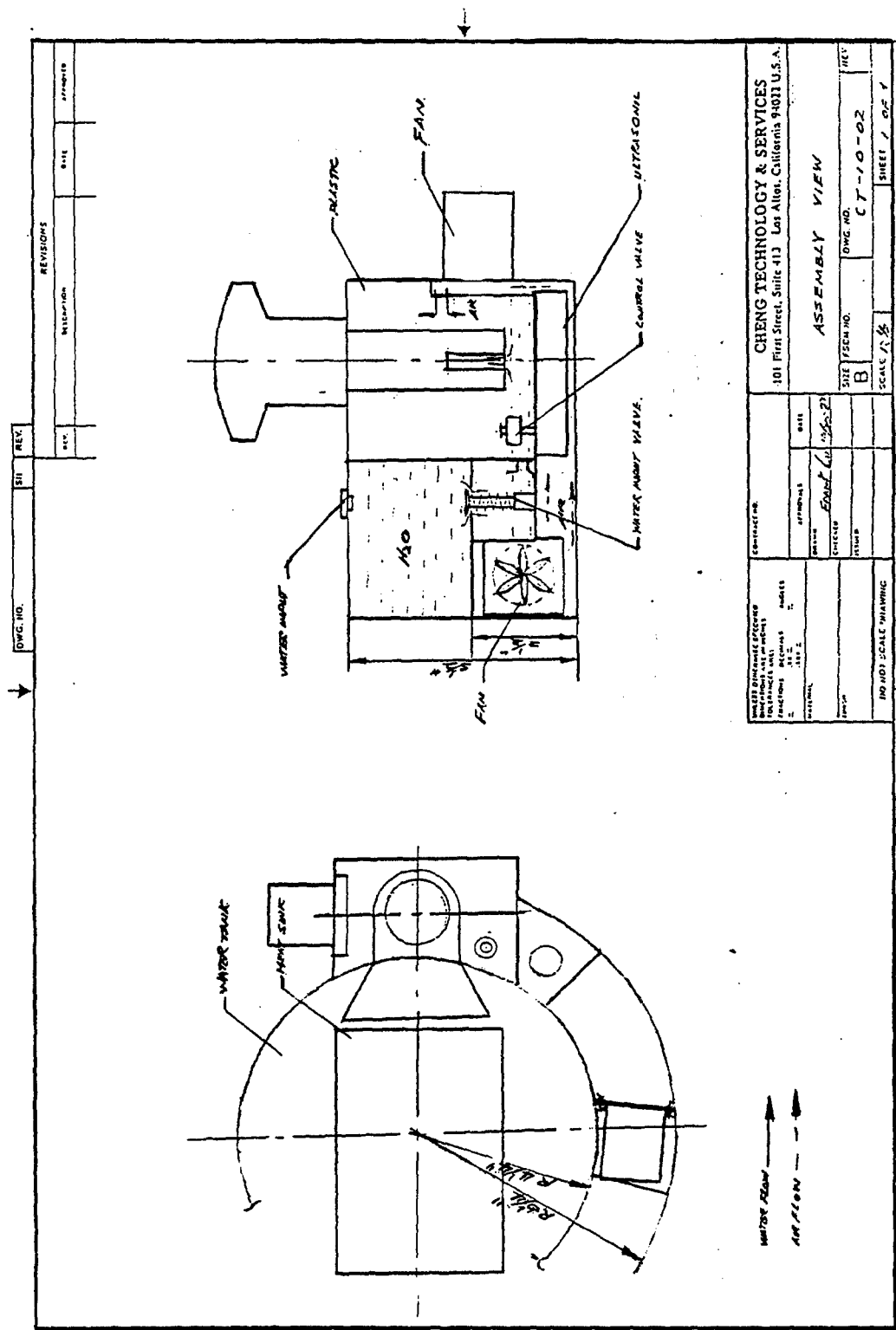


Figure 5-10 Dimensions and Layout of a Laxan Ultrasonic Cooler

5.8. Testing

5.8.1. Ambient Conditions. First, a performance baseline was established for the new compound cooling system. Thermocouple (TC) positions employed are shown in Figure 5-11. A multiple-channel TC recorder was used to record the data. The ambient temperature on the day of the test was 59 °F. The test of the unit was performed to see how effective the TEC is with a heat pipe as a cooled finger. The 1-gallon plastic foam-insulated container was filled with a warm water at around 98 °F. The selected relevant test data are presented in Figure 5-12. The cooling rate recorded was very fast and the water reached 70 °F in about 2 hours with only about 82 watts of power input. Actually in the first hour, the water temperature was dropped from 98 °F to 77 °F. This means 168 Btu were removed from water, or an equivalent of 53.5 watts of cooling with 82 watts of power input. The apparent performance is better than expected because of the fact that the plastic-foam-insulated container probably lost heat to the surrounding air due to its poor insulation quality. The highest heat rejection temperature was at about 114 °F, and the cooled surface temperature had an average 24 °F temperature difference.

5.8.2. Simulated All-buttoned-up Combat Conditions. The most important tests involved the simulation of the combat environment. This series of tests was carried out in the environmental chamber facility leased from Quanta Corporation, whose business is the testing of customer-designed products. The environmental chamber temperature and humidity can be computer-controlled to meet the testing needs. Photographs of the testing chamber can be seen in Figures 5-13 and 5-14. The power supply and the multichannel temperature recorder for the water cooling system and its instrumentation were located outside of the chamber and are shown in Figures 5-15 and 5-16. The compound cooling system mounted on the water container is shown in Figure 5-17. Additional insulation materials were put on the outside of the cooling fins, because the chamber temperature could be higher than the fin temperature for this system.

In Figure 5-18, temperature plots taken during a 3-hour test period are presented for the purpose of comparing the effectiveness of the compound cooling system. The plots are the transient test chamber temperature, the highest heat rejection temperature of the cooling fins, the recorded actual wet bulb temperature and the cooling air exit temperature. During the first 30 minutes, the test chamber temperature and the recorded wet bulb temperature increased very rapidly. The test chamber temperatures started to

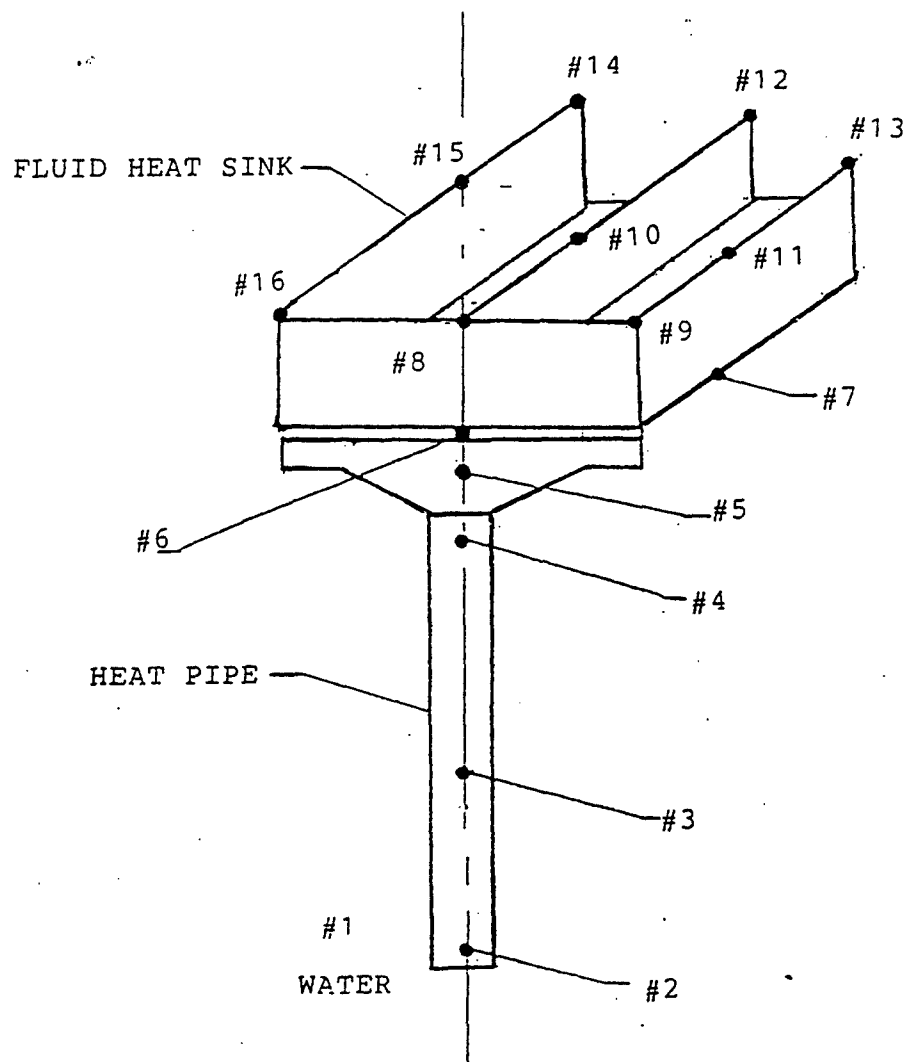


Figure 5-11 Cooling System Showing Thermocouple Positions for Environmental Chamber Tests

TEMPERATURE VS TIME

3.61 AMP. ULTRA-SONIC COOLER OFF

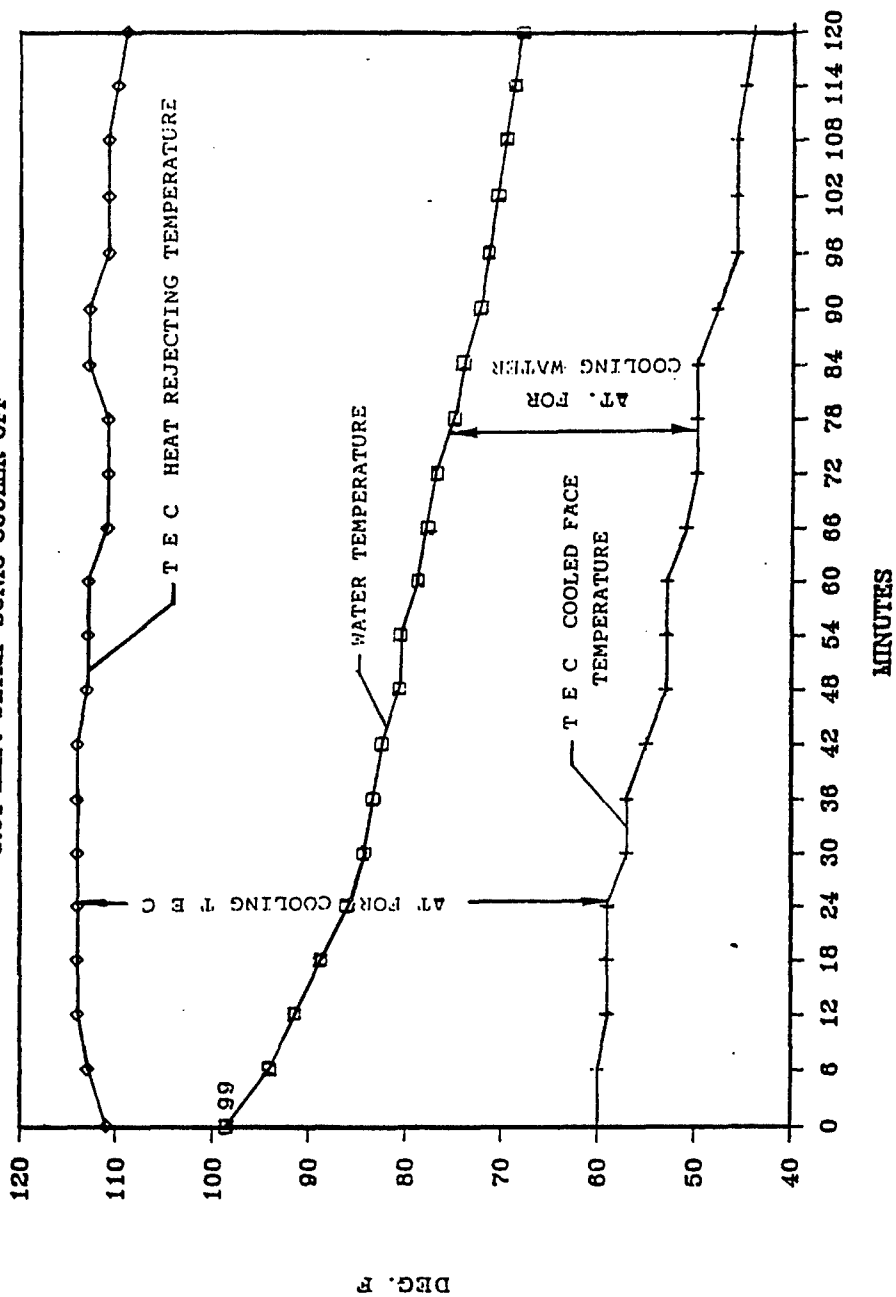


Figure 5-12 Selected Relevant Test Data

stabilize in 1 hour. In the meantime, the heat rejection temperature of the TEC responded very sharply; it increased from 120 °F to 150 °F in 24 minutes and remained almost constant afterwards. The cooling air passing through the ultrasonic evaporator responded even faster. It first increased from 90 °F to 105 °F in 16 minutes and became stable afterwards. The cooling air temperature remained approximately 15-20 °F below the wet bulb temperature, which is a phenomena not obtainable by the wicking evaporating system.

It became apparent that the heat rejection temperature responded to the cooling air temperature of the ultrasonic evaporator rather than the chamber temperature, and that is why the temperature reacted so quickly. After the system was stabilized some tweaking of the ultrasonic power was tested. When the ultrasonic power was more energetic, the cooling air temperature dropped. Some moisture could be seen exiting the cooling fin area. This means that the effectiveness of cooling was increased by the latent heat of the droplets, and the amount of water consumption was also increased. It can also be observed that the heat rejection temperature of the cooling fins sometimes was higher and sometimes lower than the chamber temperature. The average temperature difference between the cooling air and the heat rejection temperature was 45 °F.

Finally, at 144 minutes, the power of the ultrasonic system was turned off. The cooling air temperature immediately rose and the heat rejection temperature of the TEC increased beyond its normal operating range.

In Figure 5-19, the temperature histories of another test sequence are presented. In the data, it may be seen that the effectiveness of the cooling under the room temperature condition was extremely rapid. When the chamber temperature was increased, the cooling effect slowed down. When the current of the TEC was increased, the temperature difference between the cold finger and the hot surface went beyond 60 °F between 42 to 90 minutes, the heat pumping rate went down to the point that it only balanced out this heat transferred across the container wall from the 150 °F chamber temperature and reached equilibrium. Based upon calculations from previously obtained heat transfer data, the system was still pumping 55 Btu/hour out of the water. When the current of the TEC was reduced and the temperature differences across the TEC unit were also reduced, then the water temperature dropped again. This is a well-known phenomena when using TEC units, but due to good heat rejection conditions this phenomena was encountered at room temperature. In practice it rarely is observed. This only

means that during the Phase II prototype design, selection of the TEC will have to account for the current versus temperature difference characteristics carefully.



Figure 5-13 Environment Test Facility

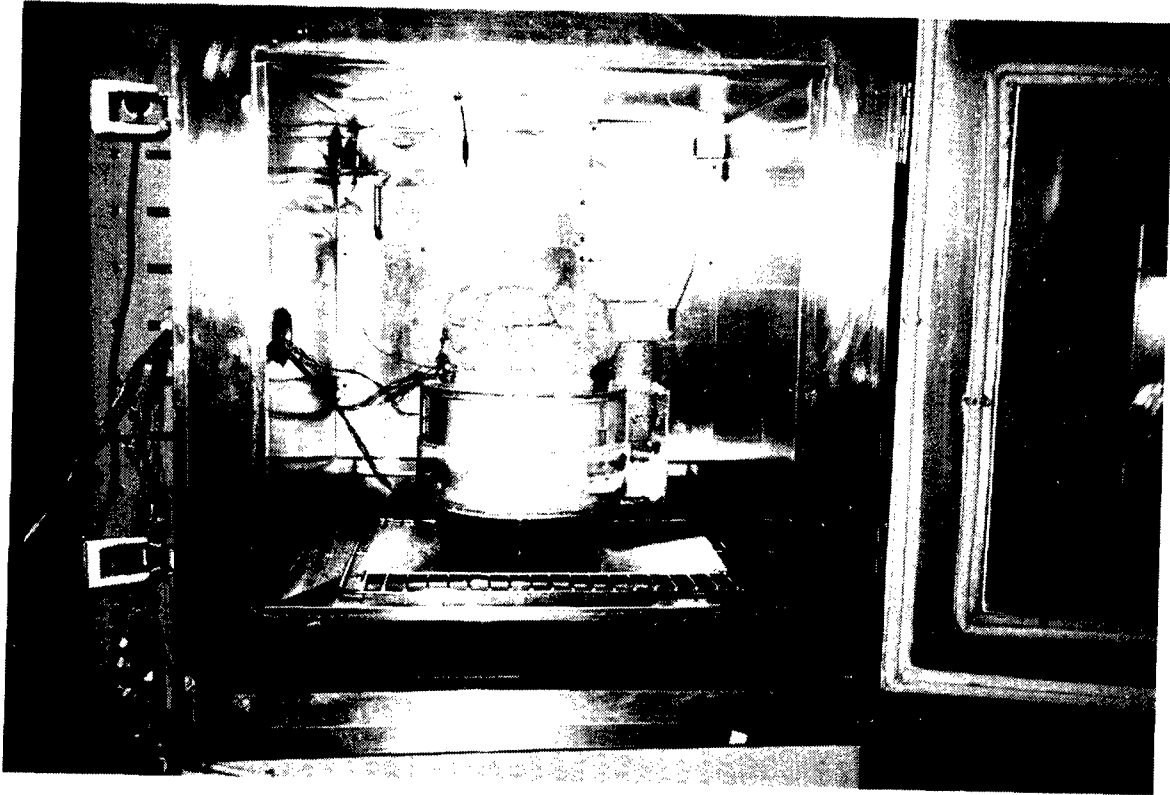


Figure 5-14 Environmental Test Chamber Interior

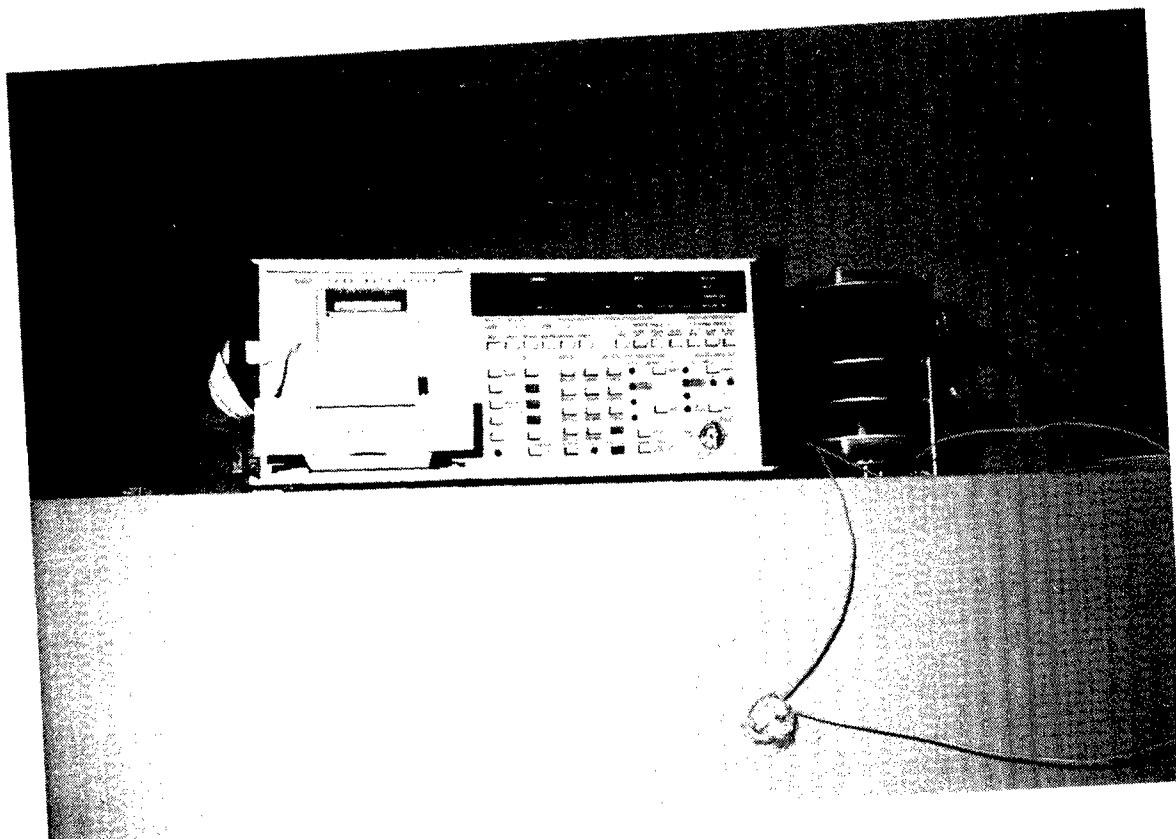


Figure 5-15 Power Supply

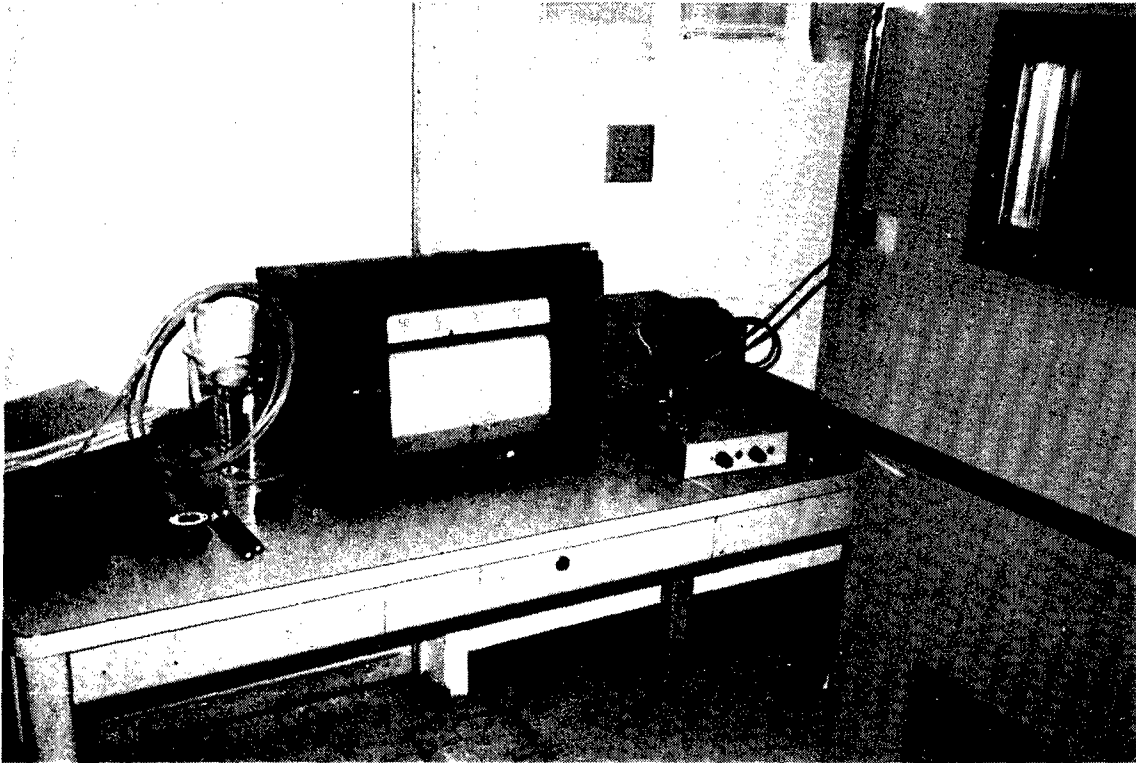


Figure 5-16 Multi-channel Temperature Recorder

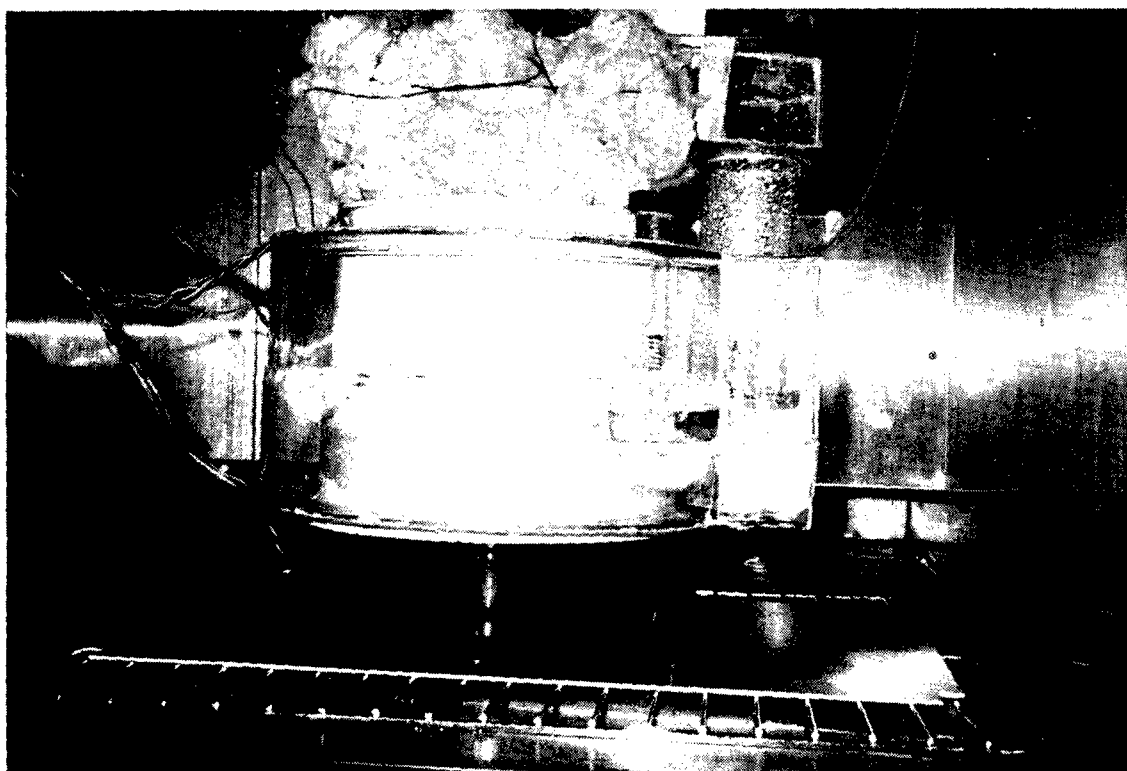


Figure 5-17 Compound Cooling System Installed on Water Container

TEMPERATURE VS TIME

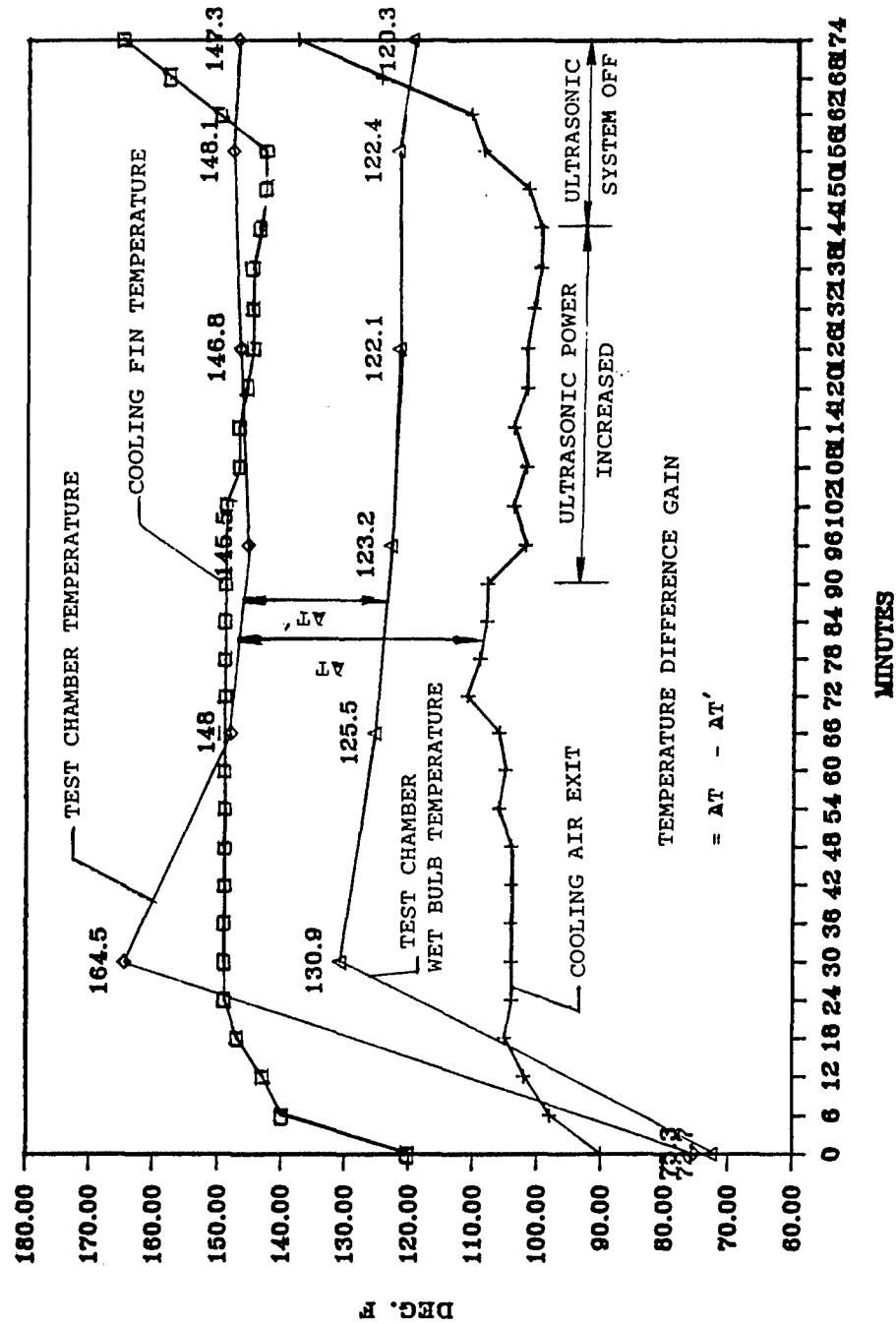


Figure 5-18 Effectiveness of Ultrasonic Cooler as Shown by Test Temperature Histories

TEMPERATURE VS TIME

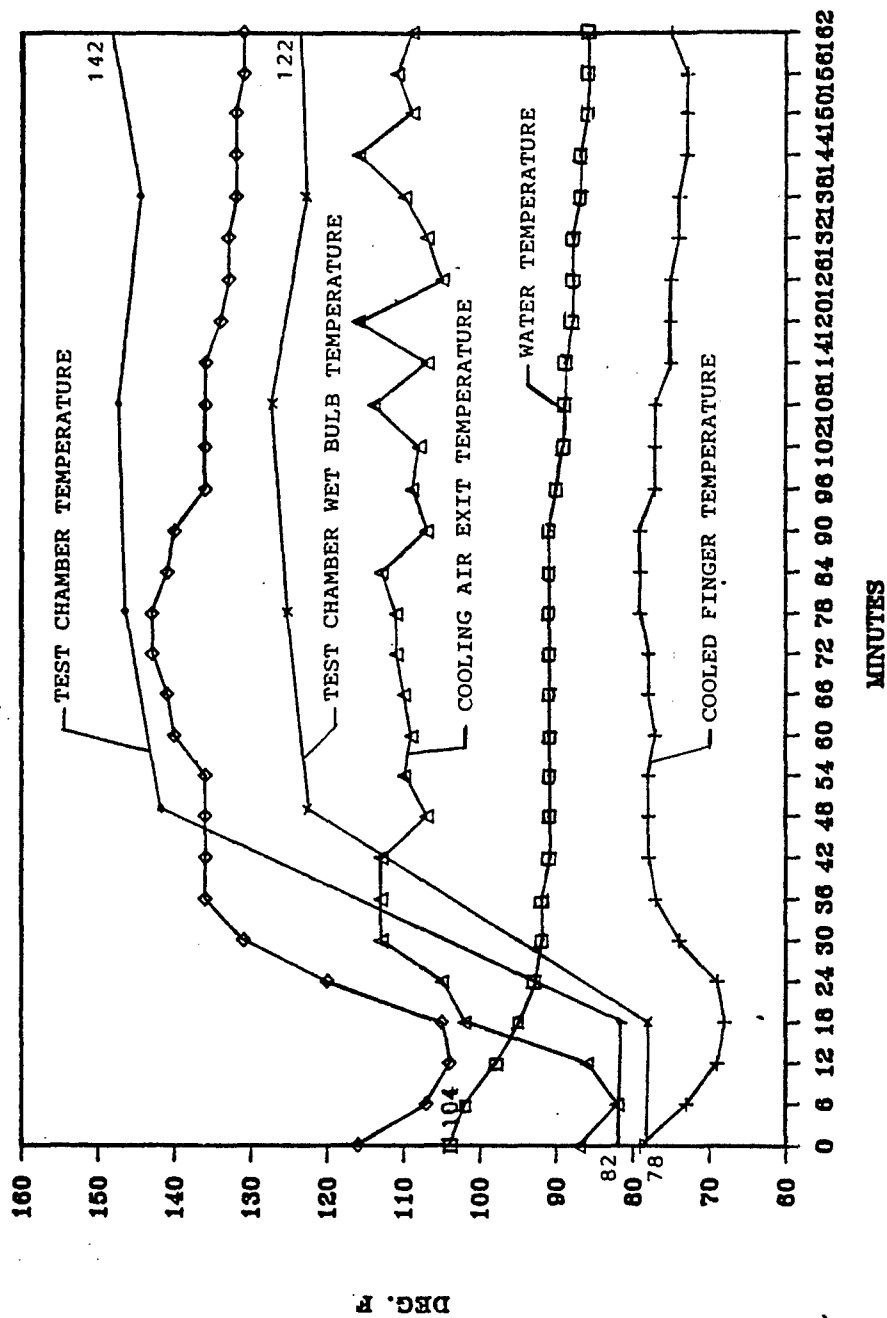


Figure 5-19 Complete System Test Temperature Histories

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